Conseil national de recherches Canada | National Research Council Canada

Institut de génie des matériaux | Industrial Materials Research Institute

75, De Mortagne, Boucherville, Qué., Canada J4B 6Y4
(514) 641-2280

IGM87RT-202-557-G
CNRC 27569

Réference File

EXPERIMENTAL LAKE AREA ATMOSPHERIC CORROSION PROGRAM

REPORT FOR THE PERIOD DECEMBER 1984 - NOVEMBER 1985

J.-J. HECHLER, J. BOULANGER, D. NOËL

February 1987

Canada

I. INTRODUCTION

The Experimental Lake Area, near Kenora, Ontario was chosen in July 1984 to serve as a baseline site for the atmospheric corrosion program of the U.S. Bureau of Mines, Avondale, which is part of the U.S. National Acidic Precipitation Program. This work is part of the Canadian Long Range Transport of Airborne Pollutants (LRTAP) research program (project #308) and also one of the joint U.S.-Canadian research project related to transboundary air pollution. With help from Departments within Environment Canada and the Ministry of Oceans and Fisheries Canada, work began at E.L.A. on December 1st, 1984. This report gives the results of the first year of testing (December 1984 - November 1985).

II. PROGRAM

Two types of samples have been exposed: 4" X 6" weight loss samples and 1" X 1¼" surface analysis samples. Due to a delay in obtaining zinc, only the following metals have been exposed during the first year: mild steel, galvanized steel, galvalume, copper, aluminium and weathering steel. There were five exposure periods: December 1984-February 1985 (Period 1), March-May 1985 (Period 2), June-August 1985 (Period 3), September-November 1985 (Period 4) and December 1984-November 1985 (Period 5), i.e. four three-month periods and one one-year period.

Two nitration and two sulfation plates were exposed for periods of one month during the whole year. Two humidity sensors (Sereda type) were mounted on the testing rack to measure the time-of-wetness. The site being part of the Canadian Air and Precipitation Monitoring Network (CAPMON), the following atmospheric data are available: precipitation (depth and chemical analyses), wind speed and direction, temperature, relative humidity, sunshine hours, air quality (SO_x, NO_x, TSP).

III. EXPERIMENTAL

1) Site

ELA is located in western Ontario (lat 49° 39'N, long. 93° 43'W, alt. 358 m), approximately 100 kms east of the Ontario - Manitoba border, 30 kms south of the Trans-Canada Highway in an inhabited area. The only local source of air pollution is a diesel power generator, located around 1 km south of the atmospheric corrosion rack, which might be of some influence since the wind comes from the south about 8-9% of the time. The rack is well exposed on top of a hill within 10 metres of all the meteorology instruments (Figure 1).

ELA is a research station of the Ministry of Fisheries and Ocean of Canada with a staff of around 40 people between April and October. From November to March, the site is supervised by one or more people living on the site.

2) Materials tested

The materials exposed are described in Table I (a) and (b).

3) Sample preparation before exposure

All samples were cut and machined to 4" by 6" and 1" by 1½", including galvalume and galvanized steel. They were chemically cleaned and treated as mentioned in the Bureau of Mines Quality Assurance Document. The only differences are: the Rhodine inhibitor is replaced by 2-butyne-1,4-diol and the mild steel and Corten steel surface analysis electropolishing solution is a H_2SO_4 - H_3PO_4 - CrO_3 - H_2O mixture instead of an acetic acid - perchloric acid mixture.

All samples were weighed to 0.1 mg except the Corten and the mild steel samples which could only, for the first year, be weighed to 10 mg.

4) Sample exposure

All samples were exposed in triplicate according to standard ASTM practice (G-50). The bolt holding the microanalysis samples was close to their lower edge in order to avoid staining of the sample by run-offs from around the bolts. All samples were removed and installed by IMRI personnel.

5) Sample cleaning after exposure

All weight-loss samples and all cleaning solutions obtained were treated as stated in the Bureau of Mines Quality Assurance Document. Since only traces of undissolved solids (too small to be analysed) are present in these solutions, they were not filtered. The only problem that arose during the evaporation of the solutions is the precipitation of zinc ions from the galvanized steel solution. Since all samples from the first year were treated at the same time, no zinc was therefore found in the corresponding solutions. Table 2 gives the blank weight loss values for the cleaning solutions used to correct the sample weight losses.

6) Metal analysis in the cleaning solutions

Atomic absorption spectroscopy was used for the following analyses:

Fe	Carbon steel and Corten
Cu	Copper
Al	Aluminium
Zn, Fe	Galvalume, galvanized steel.

For calibration, solutions of known quantities of each ion with the same matrices as the solutions to be analysed were used. For all metals, unexposed samples were cleaned according to the same procedure as for exposed samples; the metal content in these cleaning solutions was used as the blank value and subtracted from the total metal ion content found for the exposed samples. These values were close to the blank weight loss values.

7) Sulfur analysis in the cleaning solutions

Ion chromatography has been tried to determine $SO_4^{=}$ in the cleaning solutions. This technique is only applicable to neutral or slightly acid solutions. This is the case for the cleaning solutions after evaporation for galvanized steel, copper and aluminium depending on the degree of evaporation. Further neutralizing of these solutions and those corresponding to the mild steel and Corten leads to precipitation, preventing any further analysis. No satisfactory results have been obtained. The modified Eschka method has thus been used on carbon steel and weathering steel.

8) Sulfation and nitration plates (Serco)

The nitration plates were analysed according to the standard SERCO method (colorimetry). The turbidimetry method used for the sulfation plates gave absorbance values too small to be precise, and modified methods did not improve the results. Ion chromatography methods have thus been developed.

9) Time-of-wetness

A data acquisition system was developed to measure and store the voltage of one sensor every 5 minutes and to measure continuously the time for which this voltage exceeds 10 mV. Two such systems were installed at the site (Figures 2 and 3).

Two carefully selected sensors were used. From December '84 to September '85, the two sensors were exposed skyward glued on an aluminium plate. During this period, some problems were experienced and modifications had to be made, but one of the systems was always working. After September '85, both systems worked properly so one of the sensors was put on the groundward side of the aluminium plate in order to have the time-of-wetness (TOW) also on the groundward side of the panel.

IV. RESULTS

1) Weight loss samples

Table III gives the total corrosion thickness (in µm and in µm/year of wetness) for the five exposure periods. Tables IV to IX give the details.

1.1) Aluminium (table IX)

The measured weight losses are all between zero and 2 mg. These values are not much larger than the experimental error (0.5 - 1.0 mg). Therefore, the corrosion thicknesses have at least 50% error. They can practically be considered as zero, being of the order of 0.01 to 0.05 µm/year.

1.2) Copper (Table VIII)

Significant corrosion occurs with weight losses ranging from 35 mg to 307 mg/plate. The ratio "corrosion products (including adsorbed water) over metal in corrosion products" is close to the value of the other sites (1.06-1.19). The corrosion rate per year of wetness is much lower in summer than during the other periods. The ratio of the "metal in the corrosion products over the weight loss" is close to 1, showing no appreciable run-off of the corrosion products by rain.

1.3) Galvanized steel - (Table VI a and b)

The content of zinc in the corrosion products could not be analysed, therefore the corresponding columns of Table VI are empty. Since the galvanized steel (and galvalume) plates have been machined, steel is exposed at the edges. On visual examination, this corrosion of the edges can be seen but seems smaller than the corrosion occurring on the carbon steel samples. Table VI (a) gives the corrosion values not taking into account this corrosion.

In Table VI (b), an approximate correction has been made based on the following hypothesis:

- The nature and the mass of the corrosion products per surface unit is the same for the edges of the galvanized steel as for the mild steel samples during the same period of exposure.

- These products are not removed during the cleaning of the galvanized steel (this has been verified by visual examination).

- The products are FeOOH and the % of run-off is the same on these two surfaces.

An exact correction would have also taken into account the quantity of steel lost corresponding to the corrosion products lost by run-off, whose value is unknown. Therefore, no correction was made for the corrosion products mass. The approximate correction for the metal weight loss is the increase of the mass of "OOH" corresponding to the formation of FeOOH on the edges. If for the same period m_s is the weight of the corrosion products on the steel sample, then the mass of the corrosion products on the edges of the galvanized steel is:

$$m_g = m_s \frac{\text{Area of the edges}}{\text{Total area of the carbon steel sample}} = 0{,}0113\ m_s$$

$$\text{the corresponding "OOH" is } m'_g = m_g \frac{33}{89} = 0{,}0042\ m_s$$

These values have to be added to the weight loss reported in Table VIa. This correction corresponds roughly to an increase of 15% of the galvanized steel corrosion. Values of the ratio "corrosion products over weight loss" are very low compared to the other sites, except for the first two values which are 1.44 and 1.50. So, it seems that except for the winter period, run-off from the sample seems important.

1.4) Galvalume (Table VIIa and b)

Results are presented in Table VIIa without correction for the corrosion of steel at the edges. Corrosion on these edges seems to be more important here than for galvanized steel. During the stripping with CrO_3 almost all the iron oxides are dissolved for the 3-month samples, but remain in appreciable quantity for the 1-year sample. Thus, a correction which can be made for the 3-month sample is to analyse the Fe in the stripping solution. The mass of Fe found is then subtracted from the panel weight loss in order to get a corrected weight loss. This correction is again an approximation since the iron lost in the run-offs cannot be known. The FeOOH mass corresponding to this mass of Fe is also subtracted from the corrosion products mass. These corrections have been made in Table VIIb. No correction has been made for the 1-year sample.

This correction decreases the corrosion weight loss by around 10-20%. Corrosion values are small, close to 0.3 µm/year or 2 µm/year of wetness.

1.5 Carbon steel and weathering steel (Table IV and V)

As for the other sites, weathering steel corrodes faster than carbon steel for short exposure periods. The ratio "corrosion products over metal in the corrosion products" is higher than for the other sites. This is due to a higher content of water. Samples from the second year of exposure contained between 7% and 12% of water in these products (weight loss at 90°C during 24 hours).

2) Surface analysis samples

IR, RAMAN, X-RAY, SEM, electrochemistry work was planned to be done on these samples but manpower was and is still not available. Identification of the nature of the corrosion products by X-Ray diffraction is planned in the near future. PIXE analyses are currently underway at the Université de Montréal (see p. 11).

3) Time-of-wetness

Having no previous experience with the Sereda sensors, from December '84 to September '85, the two sensors were selected only according to the ASTM G'84 criteria. It appeared that for that period of time, the voltages delivered by the two sensors were, at times, very different resulting in very different values of TOW. For instance, for May 1985, the TOW obtained were 189.5 and 95.0 hours. The TOW value retained was the highest value, corresponding to the sensor delivering the highest voltage and, therefore, having the best sensitivity. The sensors were changed every three months. The most sensitive sensor for the two first periods (December-February, March-May) displayed the same highest voltage

(~ 180 mV) so their TOW can be compared. The sensors used in the third period (June - Aug.) were less sensitive and displayed a maximum voltage of only around 80 mV. Thus the TOW for the third period may be undervalued when compared to the value for the first two periods. For these three periods both sensors were exposed skywards.

From September on, we chose the two sensors more carefully. Around 10 sensors were selected according to the ASTM criteria and then exposed on the roof of IMRI for 2-3 weeks; the two sensors displaying the same highest voltage within a few millivolts were selected and exposed at ELA. They also give the same TOW within 10%. Being identical, one was then exposed skywards and the other groundwards. These two sensors displayed around 180 mV as the highest voltage and were then comparable to the two sensors used for the TOW values during the first two periods. The TOW values are given in Tables X (a) and X (b). In order to better understand the meaning of this TOW and the errors involved, we are currently studying a population of 40 sensors exposed on the same rack in Montreal.

Table X (a) and X (b) give also the ISO TOW (RH > 80% and $t^0 > 0°C$). The two TOW follow different variations. The electrochemical TOW increases from January to May, than decreases to July, increases again to September then decreases again. This shows clearly the usual pattern: high humidity in Spring and Autumn and low humidity in Summer and Winter. The ISO TOW increases constantly from January to August and then decreases constantly to December. Over one year, the ISO TOW is roughly double the electrochemical TOW. The corrosion values per year of wetness are given in Table XI.

It can be seen that for the electrochemical TOW, the corrosion value for period 5 (one year) is very close to the mean value of the four other periods. Period 3 (Summer) gives the highest corrosion rate for the weathering steel and the lowest for copper, the carbon steel having an intermediate value.

For the ISO TOW, the mean corrosion values of the 3-month periods is close to the one-year period value if the winter period is left out. This means probably an ISO TOW value much too small during the winter period (malfunctioning of the hygrometer?). Here, the smallest corrosion values are obtained for period 4 (Autumn) for weathering steel and carbon steel. Period 3 (Summer) gives again the lowest corrosion rate for copper.

4) Sulfation and nitration plates

Sulfation and nitration plates were exposed monthly in duplicate on plastic holders from SERCO and analysed according to the usual methods: colorimetry for NO_2^- and turbidimetry for $SO_4^{=}$.

A first series of nitration plates (Dec. 1984-Aug.1985) gave values of 10-25 µg NO_2^-/plate including a blank of 20 µg/plate. A second series (Sept. 1985-May 1986) gave values of 1-2 µg NO_2^-/plate including a blank of 4 µg NO_2^-/plate. Considering the values of the blanks, the mass of NO_2^- adsorbed by the plate is zero. In spring '86, we started to use ion chromatography. The value for NO_2^- was lower than our detection limit which corresponds to ~ 5 µg NO_2^- in terms of µg/plate. This confirms the zero values obtained by colorimetry. This technique gives also NO_3^-: we found values of 60 - 130 µg NO_3^-/plate (blank values = 0)! It seems that NO_2^- is present in the plate in much smaller quantities than NO_3^-. Future analysis of other nitration plates will help to clarify this point.

Concerning the sulfation plates, due to the unsuccessful use of turbidimetry, there are no values for December 1984 to September 1985. With ion chromatography, values for October and November 1985 were obtained and are given in Table XVII. These values increased to around 0.5 µg/cm^2.d in January 1986 and decreased to zero in April and the following months.

A detailed study of these two passive monitors is currently underway to better evaluate the meaning and the errors associated with the results.

5) Sulfur analysis in the corrosion products of carbon steel and weathering steel

Results are given in Table XII. Three freshly prepared weathering steel samples were cleaned and the residue after evaporation was used as a blank. After the unsuccessful attempts to use ion-chromatography on the September-November 1985 samples, there was not enough mass left for analysis. Values for period 1 (December 1984 - February 1985) are certainly much too high: recent PIXE analysis on the corresponding surface analysis samples gave values of 1.2 mg/plate for weathering steel and 0.6 mg/plate for mild steel. These values are confirmed by the values obtained by the Eschka method for the second year samples: 5-8 mg/plate for the one-year samples and 0-3 mg/plate for the three-months samples. Considering a blank value of 6-10 mg/plate and the determined values of 7-11 mg/plate, the corrected values are practically zero using the Eschka method, except for the one-year weathering steel samples.

V) CLIMATIC DATA

These data are given in the following tables:

Table XIII: Rain chemistry
Table XIV : Wind speed and direction
Table XV : Solar radiation, temperature, relative humidity
Table XVI : Air quality (Values of Na^+, K^+, Cl^-, NH_4^+ also available).

CONCLUSION

The following table gives the corrosion in µm/yr for 3-months periods at ELA and for 1-month period at the New York State site:

	ELA	N.Y.
Weathering steel	3.6 - 13.6	10.6 - 27.1
Carbon steel	(2) - 4.4	3.2 - 18.9
Copper	1.2 - 4.0	3.2 - 9.9
Aluminium	0.0 - 0.2	0.0 - 0.4
Galvanized steel	0.20- 0.24	0.24- 2.11
Galvalume	0.24- 0.36	0.00- 1.21

The values obtained at ELA are lower than the least corrosive site in the U.S., the New York site. A rapid glance at the air quality and precipitation chemistry also shows lower value of pollutants. Thus ELA seems to fulfil its requirements as a baseline site.

ACKNOWLEDGMENT

This work was carried out with help from:

B. Harvey (sample preparation and cleaning)
A. Pilon (wet chemical analysis)
H. Roberge (ion chromatography) at IMRI.

K. Beaty, P. and S. Sauvé, D. Holmgren at the Freshwater Institute, Ministry of Oceans and Fisheries, Winnipeg, Manitoba (general supervision at the E.L.A. site, including the climatic and meteorological instrumentation).

S. Milburn and H. Weeb of the Atmospheric Environment Service, Environment Canada, Toronto, Ontario, who provided, along with K. Beaty, the climatic and meteorological data.

D. Flinn and his group at the Bureau of Mines, U.S. Department of the Interior, Avondale, Maryland, for general information on all aspects of this program.

Special thanks to H. Martin of the Federal LRTAP Liaison Office, Environment Canada, Toronto, Ontario, for having introduced the atmospheric degradation of materials into the LRTAP Program and for his continuous effort to increase Canadian research in this area.

METALS

	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Zn	Pb	Al
1010 Carbon steel	0.13	0.36	0.01	0.012	0.018	0.05	0.02	< 0.01	0.05	0.004	0.003	< 0.01
Corten-A	0.12	0.64	0.26	0.112	0.006	0.70	0.28	< 0.01	0.28	0.007	0.003	0.040

	Mn	Si	S	Ni	Cu	Fe	Zn	Pb	Ti	Al
Copper 110	< 0.001	0.001	0.002	< 0.002	99.95+	0.001	< 0.003	0.001	< 0.001	< 0.002

	Mn	Si	Cr	Cu	Fe	Zn	Ti	Mg
Aluminium 3003 H14	0.01	0.120	< 0.01	0.01	0.24	0.02	0.05	< 0.01

COATINGS

	Mn	Si	Cr	Cu	Fe	Zn	Ti	Pb	Al	Mg
Galvanized steel	0.001	0.01	0.03	0.03	0.03	~ 99.8	< 0.001	0.04	0.02	< 0.001
Galvalume	0.001	0.30	0.01	0.1	0.07	~ 50	< 0.001	< 0.01	~ 49	0.001

CHEMICAL ANALYSIS (Weight %)

TABLE 1 (a)

ADDITIONAL INFORMATION

	MANUFACTURER'S IDENTIFICATION	MANUFACTURER
GALVANIZED STEEL	Z 275 S # 604757 Heat #172341 Gauge 0.027"	DOFASCO
GALVALUME	S # 595574 Heat # 168353 Gauge 0.018"	DOFASCO
CARBON STEEL	Serial # 584194 Heat # 170873 Grade BC 031 Gauge 0.075" Hot rolled no anneal	DOFASCO
CORTEN-A	A-606 Type 4 Hot rolled no anneal 1/16"	U.S. STEEL
COPPER	ASTM 110 - 3003 1/32"	?
ALUMINIUM	ASTM H-14 - 3000 1/16"	REYNOLDS

TABLE 1 (b)

	STRIPPING TIME (min.)	CORRECTION (mg) for 2 min.
GALVANIZED STEEL	2	5.0
GALVALUME	2	0.0
ALUMINIUM	2	0.8
COPPER	2	5.0
CORTEN-A	2	6
CARBON STEEL	2	4

BLANK WEIGHT-LOSS VALUES

TABLE 2

CORROSION THICKNESSES

PERIOD	WEATHERING STEEL		CARBON STEEL		GALVANIZED STEEL		GALVALUME		COPPER		ALUMINIUM	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Dec. 84 - Feb. 85	0.9	29	(0.5)	(15)	0.05	1.6	-	-	0.7	23	0.05	1.5
March 85- May 85	2.1	61	1.1	37	0.06	1.7	0.09	2.8	0.6	18	0.04	1.6
June 85 - Aug. 85	3.4	102	1.0	28	0.06	1.7	0.06	1.9	0.3	9	0.00	0.0
Sept.85 - Nov. 85	2.1	38	0.6	10	0.06	1.1	0.09	1.7	1.0	18	0.03	0.5
Dec. 84 - Nov. 85	9.0	57	5.7	36	0.25	1.6	0.29	1.9	2.2	14	0.015	0.1

(a) TOTAL CORROSION THICKNESS DURING THE PERIOD (µm)

(b) TOTAL CORROSION THICKNESS RATE (µm/YEAR OF WETNESS)

Table III

WEATHERING STEEL

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Fe IN Cor.products (mg/plate)	CORR.PRODUCT / Fe in Cor.products	Fe IN C.P. / Weight loss
Dec. 84 - Feb. 85	100 90 140 } 110	0.9	3,6	29	230 200 250 } 230	131 128 129 } 123	1,9	1,1
March 85 - May 85	240 270 270 } 260	2.1	8,5	61	630 600 580 } 600	269 286 281 } 279	2,1	1,1
June 85 - Aug. 85	410 390 450 } 420	3.4	13,8	102	650 590 690 } 640	315 274 319 } 303	2,1	0,7
Sept.84 - Nov. 85	260 260 250 } 260	2.1	8,5	38	500 500 440 } 480	265 266 237 } 256	1,9	1,0
Dec. 84 - Nov. 85	1130 1090 1030 } 1080	9.0	9,0	57	1890 1810 1740 } 1810	997 987 935 } 973	1,86	0,91

TABLE IV

CARBON STEEL

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Fe IN Cor.products (mg/plate)	CORR.PRODUCT / Fe in Cor.products	Fe IN C.P. / Weight loss
Dec. 84 - Feb. 85	- 30 - 40 - 20 } /	(0.5)	(2)	(15)	30 20 40 } 30	(51) / 21 } /	/	/
March 85 - May 85	150 140 140 } 140	1.1	4,6	37	170 160 160 } 160	74 79 94 } 82	2,0	0,6
June 85 - Aug. 85	130 110 110 } 120	1.0	3,9	28	140 120 120 } 130	74 77 69 } 73	1,8	0,6
Sept.85 - Nov. 85	(30) 60 80 } 70	0.6	2,3	10	140 150 190 } 160	68 71 97 } 79	2,0	1,1
Dec. 84 - Nov. 85	690 680 690 } 690	5.7	5,7	36	1220 1150 1180 } 1180	640 626 636 } 634	1,86	0,92

TABLE V

GALVANIZED STEEL

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Zn Cor.products (mg/plate)	CORR.PRODUCT Weight loss	METAL IN C.P Weight loss
Dec. 84 - Feb. 85	- 7.8 2.9 } 5.4	0.05	0,20	1.6	- 11.7 4.2 } -	- - - } /	- (1.50) (1.44)	/
March 85 - May 85	6.7 5.4 7.3 } 6.5	0.06	0.23	1.7	4.1 3.3 4.2 } 3.9	- - - } /	0.60	/
June 85 - Aug. 85	7.7 6.0 5.1 } 6.3	0.06	0.23	1.7	5.2 6.9 4.9 } 5.7	- - - } /	0.90	/
Sept.85 - Nov. 85	4.5 6.1 8.8 } 6.5	0.06	0.23	1.1	4.0 7.0 9.5 } 6.8	- - - } /	1.05	/
Dec. 84 - Nov. 85	24.9 29.5 29.2 } 27.9	0.25	0.25	1.6	15.3 13.4 13.4 } 14.0	- - - } /	0.50	/

TABLE VI (a)

GALVANIZED STEEL (with correction)

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO.RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	METAL IN Cor.products (mg/plate)	CORR.PRODUCT / Weight loss	METAL IN C.P Metal in / Weight loss
Dec. 84 - Feb. 85	7.9 3.0 } 5.5	0.05	0.20	1.6	11.7 4.2		1.48 1.40	
March 85 - May 85	7.2	0.07	0.26	1.9	3.9		0.5	
June 85 - Aug. 85	6.8	0.06	0.25	1.8	5.7		0.8	
Sept.85 - Nov. 85	7.2	0.07	0.26	1.2	6.8		0.9	
Dec. 84 - Nov. 85	32.9	0.30	0.30	1.9	14.0		0.4	

TABLE VI (b)

GALVALUME

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Zn Corr.product (mg/plate)	CORR.PRODUCT / Zn in Corr. prod.	Zn in C.P. / Zn in Weight loss
Dec. 84 - Feb. 85	- 0.1 - 0.2 / - 0.4	/	/	/	0.4 3.6 / -1.2	- 5.6 } / 0.6	/	/
March 85 - May 85	(-3.3) 6.6 } 5.0 3.3	0.09	0.34	2.8	< 0 /	2.7 1.7 } 1.9 1.3	/	/
June 85 - Aug. 85	5.5 4.5 } 3.7 1.2	0.06	0.26	1.9	2.9 1.5 } 2.1 1.9	1.2 0.7 } 0.9 0.9	2.3	0.5
Sept.85 - Nov. 85	6.8 3.4 } 5.5 6.3	0.09	0.38	1.7	3.3 5.2 } 4.2 4.1	3.0 1.8 } 2.5 2.7	1.7	0.9
Dec. 84 - Nov. 85	14.4 17.6 } 16.8 18.5	0.29	0.29	1.9	8.9 10.6 } 9.6 9.2	5.0 3.7 } 4.3 4.2	2.2	0.5

TABLE VII (a)

GALVALUME (with correction)

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Zn IN Corr.product (mg/plate)	CORR.PRODUCT / Zn in Corr. prod.	Zn in C.P. Zn in Weight loss
Dec. 84 - Feb. 85	- 0.7 - 2.3 / - 0.4	/	/	/	- 2.4 } / -1.4	- 5.6 } / 0.6	/	/
March 85 - May 85	(-4.1) 6.0 } 4.4 2.7	0.08	0.30	2.4	<0 /	2.7 1.7 } 1.9 1.3	/	/
June 85 - Aug. 85	- 3.9 3.9 (0.5)	0.07	0.27	2.0	- 0.5 } 0.6 0.7	1.2 0.7 } 0.9 0.9	/	0.5
Sept.85 - Nov. 85	5.2 1.8 } 3.9 4.8	0.07	0.27	1.2	0.6 2.5 } 1.6 1.6	3.0 1.8 } 2.5 2.7	/	1.3
Dec. 84 - Nov. 85	14.4 17.6 } 16.8 18.5	0.29	0.29	1.9	8.9 10.6 } 9.6 9.2	5.0 3.7 } 4.3 4.2	2.2	0.5

TABLE VII (b)

COPPER

PERIOD	WEIGHT LOSS (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Cu IN Corr.product (mg/plate)	CORR.PRODUCT / Cu in Corr. prod.	Cu IN C.P. / Weight loss
Dec. 84 - Feb. 85	99.2 102.1 99.4 } 100.2	0.73	2.9	23.3	118.1 121.9 121.4 } 120.5	99.4 103.9 100.8 } 101.0	1.19	1.01
March 85 - May 85	73.6 94.3 95.6 } 87.8	0.64	2.5	18.2	76.2 99.8 101.3 } 92.4	63.7 85.1 87.4 } 78.7	1.17	0.90
June 85 - Aug. 85	35.9 42.9 40.9 } 39.9	0.29	1.2	8.6	34.7 42.7 39.6 } 39.0	32.4 38.3 33.8 } 34.8	1.12	0.87
Sept.85 - Nov. 85	142.1 139.0 138.2 } 139.8	1.01	4.0	18.1	159.2 154.2 154.0 } 155.8	137.7 134.3 135.5 } 135.8	1.15	0.97
Dec. 84 - Nov. 85	306.9 305.9 298.5 } 303.8	2.20	2.20	14.1	334.9 333.3 324.8 } 331.0	291.7 297.4 287.4 } 292.2	1.13	0.96

TABLE VIII

ALUMINIUM

PERIOD	WEIGHT LOSS STEEL (mg/plate)	TOT.CORRO. THICKNESS (µm)	CORROSION RATE (µm/y)	CORRO. RATE YEAR WETNESS (µm/y)	CORROSION PRODUCTS (mg/plate)	Al IN Corr.product (mg/plate)	CORR.PRODUCT / Al in Corr. prod.	Al IN C.P. / Weight loss
Dec. 84 - Feb. 85	1.5 2.1 2.2 } 1.9	0.05	0.2	1.5	2.1 3.1 2.8 } 2.7	1.2 1.5 1.3 } 1.3	2.1	0.7
March 85 - May 85	2.8 1.6 (6.2) } 2.2	0.04	0.2	1.6	(-0.2) (-0.3) (-0.1) /	0.3 0.3 0.3 } 0.3	/	/
June 85 - Aug. 85	-1.2 -1.4 -0.9 } 0	0.00	0.00	0.0	- 0.1 - 0.3 - 0.2 /	0.4 0.4 0.4 } 0.4	/	/
Sept.85 - Nov. 85	1.0 1.6 1.1 } 1.2	0.03	0.1	0.5	2.1 2.2 1.4 } 1.9	0.5 0.5 0.5 } 0.5	3.8	0.4
Dec. 84 - Nov. 85	-0.4 0.4 0.8 } 0.6	0.015	0.015	0.09	- 0.1 0.5 0.8 } 0.6	0.5 0.4 0.4 } 0.4	0.7	0.7

TABLE IX

MONTH	TOW (10 mV) (hours)		ISO/TOW (Hours)	$\%\left(\frac{\text{TOW (10 mV)}}{\text{Total time}}\right)$ Skyward
	Skyward	Grounward		
Dec '84	192.1	/	20	26
Jan. '85	25.2	/	0	3
Feb. '85	55.7	/	70	8
March '85	45.0	/	40	6
April '85	83.5	/	120	12
May '85	189.5	/	220	26
June '85	111.1	/	300	15
July '85	52.8	/	290	7
Aug. '85	156.5	/	520	21
Sept. '85	170.5	71.1	490	24
Oct. '85	163.6	8.0	340	22
Nov. '85	119.1	75.2	(150)	17
Dec/84 Nov/85	1364.6	/	2560	/
TOTAL %	16%	/	30%	/

TABLE X (a)

TIME-OF-WETNESS

METAL EXPOSURE PERIODS		NUMBER OF DAYS	TOW Skyward (10 mv) (hours)	TOW ISO (hours)
No.	Dates			
1	20/11/84-26/02/85	90	273.0	- 90
2	27/02/85-29/05/85	92	306.6	- 380
3	30/05/85-28/08/85	91	294.5	- 1110
4	29/08/85-28/11/85	92	490.5	- 980
5	29/11/84-28/11/85	365	1364.6	- 2560

TABLE X (b)

TIME OF WETNESS

METAL	PERIOD	µm	µm/YEAR OF WETNESS (Electroch.)		µm/YEAR OF WETNESS (ISO)	
Weathering Steel	1	0.9	29	58	88	31
	2	2.1	61		48	
	3	3.4	102		27	
	4	2.1	38		19	
	5	9.0	57		31	
Carbon Steel	1	(0.5)	(15)	25	(49)	13
	2	1.1	37		25	
	3	1.0	28		8	
	4	0.6	10		5	
	5	5.7	36		19	
Copper	1	0.7	23	17	68	8
	2	0.6	18		14	
	3	0.3	9		2	
	4	1.0	18		9	
	5	2.2	14		7	
Galvalume	5	0.29	1.9		1	
Aluminium	5	0.015	0.1		0.05	
Galv. steel	5	0.25	1.6		1.0	

CORROSION RATES PER YEAR OF TIME OF WETNESS

TABLE XI

SULFUR IN THE CORROSION PRODUCTS

PERIOD	STEEL	S (mg/plate)	MEAN VALUE	CORRECTED MEAN VALUE
1	Carbon steel	(65, 37, 156) ?	(86) ?	(78) ?
	Weathering steel	(86) (15) ? (42)	(48) ?	(40) ?
2	Carbon steel	9, 4, 7	7 ± 2	0
	Weathering steel	6, 4, 6	5 ± 1	0
3	Carbon steel	9, 10, 11	10 ± 1	2 ± 3
	Weathering steel	11, 8, 8	9 ± 2	1 ± 4
4	Carbon steel	/	/	/
	Weathering steel	/	/	/
5	Carbon steel	7, 11, 10	9 ± 2	1 ± 4
	Weathering steel	12, 17, 14	14 ± 3	6 ± 5

TABLE XII

RAIN CHEMISTRY

PERIOD	TOTAL DEPTH (mm)	PH	H^+ (mg/1)	$SO_4^=$ (mg/1)	N (V) (mg/1)	Cl^- (mg/1)	N(III) (mg/1)	Na^+ (mg/1)	Ca^{++} (mg/1)	Mg^{++} (mg/1)
December '84	52,3	5,07	0,0086	0,53	0,15	0,04	0,05	0,04	0,10	0,02
January '85	24,8	4,74	0,0180	0,47	0,21	0,04	0,02	0,07	0,10	0,01
February '85	19,5	4,43	0,0368	0,65	0,39	0,05	0,16	0,03	0,10	0,01
March '85	12,9	4,73	0,0185	4,52	0,96	0,15	1,11	0,13	0,96	0,08
April '85	112,5	(4,75)	(0,0176)	(0,66)	(0,12)	(0,03)	(0,161)	(0,02)	(0,15)	(0,03)
May '85	145,1	4,90	0,0123	0,96	0,22	0,03	0,22	0,03	0,31	0,04
June '85	130,7	5,01	0,0097	0,78	0,16	0,05	0,16	0,02	0,23	0,03
July '85	41,5	4,94	0,0115	1,06	0,33	0,09	0,42	0,05	0,33	0,05
August '85	130,0	5,08	0,0083	0,66	0,13	0,06	0,16	0,02	0,06	0,01
September '85	135,3	5,29	0,0051	0,77	0,15	0,04	0,35	0,02	0,11	0,02
October '85	38,1	4,84	0,0147	0,69	0,10	0,05	0,06	0,02	0,07	0,01
November '85	41,5	4,89	0,0129	0,69	0,21	0,08	0,16	0,03	0,17	0,02

TABLE XIII

PRECIPITATION-WEIGHTED MEAN CONCENTRATION

WIND SPEED, WIND DIRECTION

PERIOD	N	NE	E	SE	S	SW	W	NW	No Wind	Prevailing	
										Direct.	Mean sp. (km/h)
December '84	10.8 6	12.2 13	7.5 5	7.7 3	12.0 13	13.4 31	8.6 9	10.9 18	0 2	SW	11.3
January '85	13.4 12	14.5 6	13.1 3	6.7 1	6.1 8	10.5 28	6.2 6	11.1 32	0 4	NW	10.3
February '85	/	/	/	/	/	/	/	/	/	/	/
March '85	10.4 9	17.6 20	15.5 8	11.5 4	13.4 13	14.3 22	9.7 4	13.2 18	0 2	SW	13.8
April '85	12.3 13	13.7 26	11.4 8	10.5 8	11.0 11	17.0 17	7.8 0	14.5 17	0 0	NE	13.6
May '85	12.2 8	13.0 26	11.2 5	12.4 11	8.2 12	13.5 21	6.1 3	14.0 13	0 1	NE	12.1
June '85	9.2 9	16.0 13	9.6 6	12.7 8	9.9 17	13.1 15	6.7 3	15.7 28	0 1	NW	12.7
July '85	11.0 13	11.8 5	5.5 2	10.0 4	9.0 10	11.1 17	8.0 8	11.8 39	0 2	NW	10.6
August '85	10.9 8	9.7 3	10.1 6	11.7 11	10.9 14	16.3 25	8.6 6	10.6 15	0 2	SW	11.7
September '85	9.8 7	13.4 25	6.5 2	11.6 6	12.7 15	15.8 25	10.3 4	13.5 15	0 1	SW	13.2
October '85	10.8 7	19.7 6	10.8 2	10.0 6	16.9 20	14.9 34	9.2 4	12.0 21	0 0	SW	14.0
November '85	10.2 8	16.4 24	8.2 6	6.6 5	11.8 15	9.3 15	8.8 8	10.8 14	0 5	NE	10.8

Note: In each rectangle having 2 figures, the upper figure is the mean wind speed (km/h), the lower is the % of time during which the wind blows in the indicated direction.

TABLE XIV - PRECIPITATION-WEIGHTED MEAN CONCENTRATION

PERIOD	SOLAR RAD. (hours)	TEMPERATURE (°C)			RH		
		Mean	Max.	Min.	Mean	Max.	Min
December '84	47.8	- 16.0	2.5	- 34.0	82	92	65
January '85	66.4	- 17.8	- 0.5	- 40.5	82	95	70
February '85	120.9	- 15.0	7.0	- 40.0	77	95	45
March '85	191.3	- 3.1	10.0	- 18.0	68	90	40
April '85	198.0	4.8	25.5	- 10.5	66	90	34
May '85	229.1	12.9	25.5	1.0	62	92	32
June '85	194.7	13.2	24.0	1.5	79	92	34
July '85	296.4	18.5	27.0	10.0	72	94	40
August '85	169.2	15.8	26.5	7.0	82	98	50
September '85	126.0	9.9	22.5	0.0	81	100	50
October '85	136.0	5.5	15.5	- 4.5	78	100	45
November '85	(130)	- 9.9	8.5	- 13.0	85	100	45

TABLE XV

AIR QUALITY ($\mu g/m^3$)

PERIOD	PARTICLES		GAS	
	NO_3^-	$SO_4^=$	HNO_3	SO_2
December '84				
January '85	0.24	1.08	0.22	1.51
February '85	0.23	1.50	0.37	1.71
March '85	0.25	1.35	0.33	1.11
April '85	0.10	1.35	0.24	0.45
May '85	0.10	1.04	0.21	0.23
June '85	0.09	0.99	0.19	0.24
July '85	0.07	0.65	0.19	0.33
August '85	0.09	1.66	0.26	0.20
September '85	0.09	1.04	0.14	0.28
October '85	0.22	0.99	0.30	0.97
November '85	0.25	1.19	0.24	1.35

TABLE XVI

MONTH	$SO_4^{=}$ µg/plate found	BLANK µg/plate	$SO_4^{=}$ µg/plate	$SO_4^{=}$ $\mu g/cm^2 \cdot d$	MEAN $\mu g/cm^2 \cdot d$
October 85	328 281	250	78 31	0.14 0.06	0.10
November 85	258 279	250	8 29	0.02 0.06	0.04

$SO_4^{=}$ IN THE SULFATION PLATES

TABLE XVII

Figure 1 - E.L.A. site (December 1st, 1984)

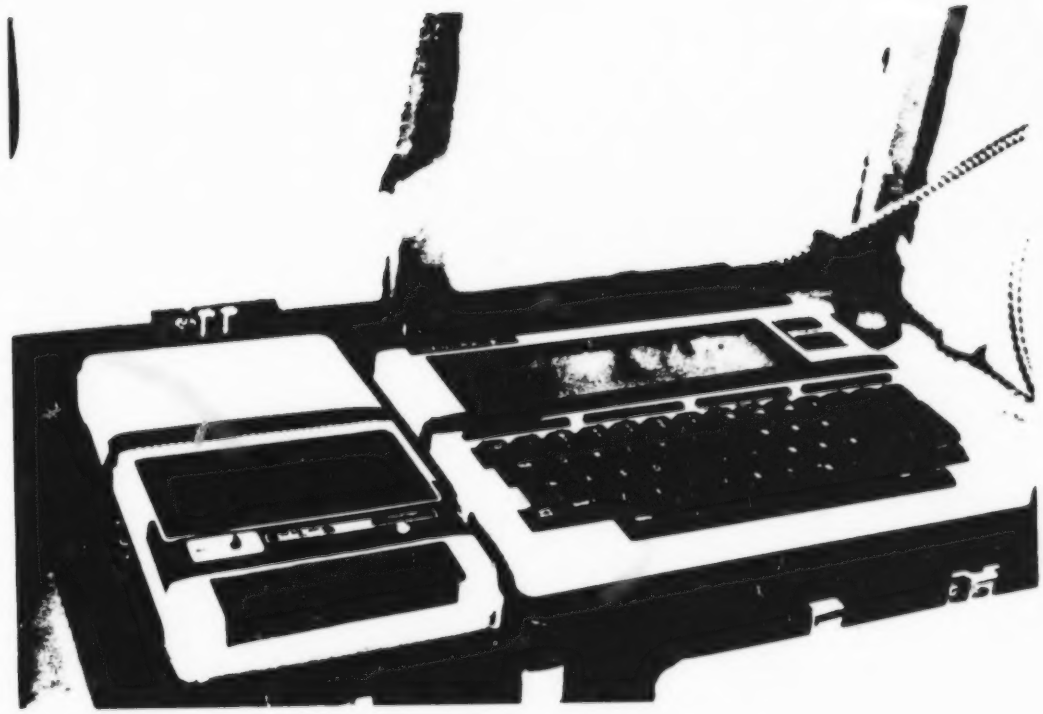

Figure 2 - TOW Data acquisition system.

Figure 3 - Example of TOW data as provided by the data acquisition system.

Emplacement de l'essai : KENORA2
Date de l'essai : 04/14/85
Nombre de points pris : 288
Heure de la premiere donnee : 0:00:07
Echantillonage : 5 min
Temps d'humidite : 594 min